A review of the support tools for the process of assembly method selection and assembly planning

T. A. ABDULLAH†, K. POPPLEWELL* and C. J. PAGE†

This paper reviews the substantial body of research into software and other tools to support the closely related methodologies of assembly system selection, design for assembly, and assembly planning. Reported research has led to the adoption of a number of tools in current use in manufacturing industry. Here, the scope of this research, and its practical applications, is considered with a view to identifying the application domain of each approach and support tool. The authors are led to the conclusion that there is a need for further research into a methodology for the initial selection of the assembly method (e.g. assembly line, fixed point assembly, etc), and that such a methodology should consider not only factors of product technology, but also the industrial environment where assembly is to take place. Further, a knowledge-based decision support tool could facilitate the application of this methodology, and expand decision support further into the selection of assembly planning methods for subsequent application.

1. Introduction

1.1. Assembly

Assembly is a very important activity in manufacturing enterprises. Wang and Li (1991) defined assembly as a ‘process of creating a connection between components or sub assemblies to form complex end products’. An assembly is composed of two or more parts or several subassemblies fixed together to form a functional product or higher level sub-assembly. Each subassembly is composed of a group of components but it is not a final product. A component is a basic part where no assembly operation occurs (Yuan and Li 2000). Nof et al. (1997) defined assembly as ‘the aggregation of all processes by which various parts and subassemblies are built together to form a complete, geometrically designed assembly or product (such as a machine or electronic circuit) either by an individual, batch or a continuous process’.

In a modern manufacturing enterprise assembly work accounts for 20–70% of the total production work with an average of 45% (Boothroyd and Dewhurst 1988, Constance 1992). Assembly costs play a significant role in overall production cost according to Riley (1982), who estimates that they often account for more than half of all the direct cost involved in manufacturing. In the automotive industry 50% of direct labour costs are due to assembly and in the precision instrument industry the proportion is 20–70%. These figures are supported by Martin-Vega and Brown (1995), who estimate that one third of the total workforce in the automotive industry
is engaged in assembly. Furthermore, assembly activity is associated with a great deal of hidden cost, such as scrap and rework (Whitney 1996).

1.2. Assembly system and process selection

As a result of high competition in today’s manufacturing world, product assembly is of great interest, and addresses activities such as process, method, system, technology etc. Zha et al. (1998b) in their paper defined an assembly process ‘as consisting of different stages such as putting together all the parts and subassemblies of a specified product, fastening, performing inspections and functional tests, labeling, separating good assemblies from bad, and packing and/or preparing them for final use’. In other words the assembly process can refer to joining, fastening, inserting, handling, and transporting, throughout the process starting from parts and progressing to subassemblies and ultimately to products, sorting in terms of quality requirements, etc.

The cost of assembling a product is related to the design of the product and its method of assembly. According to Boothroyd and Dewhurst (1992), assembly system selection should be the first step in the product development process. It is important to allow the design team to select the most appropriate assembly system for the product under consideration because it has direct bearing on the design of the product. Andreasen et al. (1983, p. 47) define an assembly system as ‘an integrated structure of machines and operators which achieves construction of sub-systems or finished products with specific characteristics, using components or if necessary, formless materials (glue, etc). This integration is achieved by using a process where the necessary operations are integrated in respect to material, energy and information’. Assembly methods or systems can be classified according to the type of equipment used for assembly. According to Andreasen et al. (1983) and Groover (1987), assembly systems can be classified into five types with regard to the degree of automation and mechanization used while assembling.

(a) Manual assembly: The work can be divided into small tasks and the tasks assigned to workstations on the line. It uses the most simple and passive auxiliary equipment, such as tables, fixtures, conveyors and hand tools. A key advantage of using manual assembly is specialization of labour.

(b) Semi-automatic assembly: Programmed machine system, where some operations are manual and some are automatic.

(c) Automatic assembly: All operations are automatically performed without human decision or intervention. The system takes decisions on the basis of the program.

(d) Flexible assembly: Manufacturing equipment builds families of related products or sub assemblies on the same set-up or with quick, automatic set-up changes. Usually, flexible equipment is associated with automatic equipment that can identify products and changes programs accordingly. Flexible assembly puts some constraints on the designers because not only do all the products have to be designed for automation, but all the parts and products must be similar enough to be built on the same machinery or work station.

(e) Adaptive assembly: A system that adapts itself automatically to certain product variations based on machine sensors and decision making algorithms, thus allowing a certain flexibility.
Boothroyd and Dewhurst (1992) developed a comprehensive suite of software, which they called ‘Toolkit’, to aid in selecting the most economic assembly system. The software module addresses two separate areas:

(a) Factors associated with equipment cost, personnel cost, levels of supervision, financial constraints, part quality and workhead down time.
(b) Factors specific to the product and its production. Values of these factors are requested for each analysis and consist of annual production volume, number of parts in the assembly, total number of parts to build all product styles, product life, number of shifts/day and assembly workers’ efficiency.

The Toolkit software is good for manual assembly analysis. However, it has limitations for semi-automatic or automatic assembly systems because analysis cannot be performed without a manual assembly analysis being in place first, thereby increasing the effort needed for specification.

1.3. Fastening and joining technologies in assemblies

Joining and fastening technologies play an important role in overall assembly. The assembly quality depends decisively on the method of joining and fastening and also the way it is carried out. Bonding is considered one of the most advanced joining methods in assembly. Traditionally riveting and welding have been used as joining methods, although at present the usage of rivets has become less important in some industries due to the benefits offered by bonding. Automotive industries such as Lotus are investigating the use of aluminium for car chassis. Lotus conducted a case study to identify which joining technologies produce better results on chassis assembly (Kochan 1996) in which they used welding and bonding techniques. It was found that bonding techniques produced better results compared with welding due to the fact that bonding enables the loads to be spread across a greater area than welding, providing strength advantages. Moreover, bonding is more precise because it eliminates the heat distortion caused by welding. The use of adhesive is the most common method of bonding, and selecting the right adhesive is a significant task due to the lack of information available when introducing a new material such as aluminium.

In contrast, Volvo and Mercedes-Benz, prefer to use laser welding for joining space frames and car body panels in preference to spot welding. Laser welding gives better tensile and fatigue strength in the welded joint, higher stiffness (by 10%), more stable and improved body tolerances and higher quality finish (Kochan 1997). Self-piercing rivets are another fastening technology ideal for use in joining dissimilar metals, aluminium panels and pre-coated panels. Self-piercing rivets have high fatigue strength and joints can be made with a high degree of reliability.

Audi has launched a new model of car that is small in size and in which all of the body of the car is made from aluminium. The body incorporates a number of manufacturing technologies, such as casting, extrusions and hydro-mechanically formed panels. Different types of joining and fastening methods are used for maximum benefit. For example, body parts are joined with laser welding and punch riveting, and the frame with self-piercing rivets. Meanwhile adhesive bonding is used to assemble the body, especially in areas where flanges are required for extra rigidity (Kochan 2000).
1.4. The art of assembly technologies in automotive, machine tool and electronics industries

The automotive and machine tool manufacturing industries are considered to be among the oldest. There are always innovations and technological changes going on in these industries. Assembly activities play an essential role in both and represent a large proportion of manufacturing cost. Different assembly paradigms and levels are involved in these industries. For example, the automotive industry is considered to be complex, referring to the complexity of assembly systems, processes and components that are involved. The design of the assembly processes employed largely reflects the very high production volumes. In contrast, different assembly paradigms apply to machine tools because, although they are also complex products with high assembly content, production volumes are lower.

The automotive industry is heavily based on a paced moving flow line that is called an assembly track, and which carries the product through a succession of working areas or stations. Production operators are each allocated a station in which to work and a predetermined list of assembly work instructions and activities. A vehicle consists of thousands of parts to be assembled. The building of various types of subassembly, such as engine, chassis, body, etc, is carried out on a moving line. Large numbers of bolts, nuts, screws etc are used in fastening processes, and various types of equipment and tools are required to conduct assembly activities. It is not an easy task to assemble automotive vehicles, and the given section of track needs a well-balanced allocation of work among operators to achieve efficient manning levels and consistent manufacture of quality products.

A similar approach is adopted in the machine tool industry. Thousands of parts are used to assemble a machine tool. Usually machine tools are heavy and require different types of handling and transporting methods for carrying out assembly activities. Different types and large numbers of bolts, nuts and screws are used for fixing and joining machine tool components. The assembly task is sometimes more complex and critical when there exists insufficient information to document each level of product assembly, perhaps because each product is customized. As a result, most machine tool assembly is carried out at a fixed point on the factory floor, with components being transported to the product—the opposite paradigm to that of automotive assembly tracks.

In another contrasting scenario, an electronic industry product, such as a mobile phone, has totally different product characteristics. It is light in weight, consists of a small number of parts, employs different types of joining and transporting methods and is entirely mass-produced. Thus, the assembly paradigm required can be expected to be different from those of the automotive and machine tool industries. Since some products have similar characteristics to each other and some do not, the question is how product characteristics can be matched to the best assembly paradigm etc to achieve a high level of production performance. Table 1 compares the most common attributes for the automotive, machine tool and electronic industries.

Due to the complexity and difficulty involved in assembling automotive vehicles and machine tools, the introduction of intelligent approaches to assembly process planning is a valuable asset to enhance the assembly activities for the above-mentioned industries. Therefore, tools such as Design For Assembly (DFA), modular assembly, etc have been established with the aim of enhancing assembly activities and improving production efficiency. This paper examines the range of support tools...
reported, and the points in the assembly design and planning activity at which they are applicable.

2. Design For Assembly (DFA)

Design For Assembly is the well-known formal analysis procedure that assesses the suitability of designs for manufacture and assembly, bringing together multidisciplinary teams to identify possible solutions. The methodology boasts many successful industrial applications over a number of years. Hundreds of industrial case studies have been published reporting the substantial benefits that have been achieved (Youssef 1994). Holbrook and Sackett (1988) also listed numerous commercial and research DFA tools. Design For Assembly should be considered at the earliest stage of the design before commitment is made to production or assembly, thereby avoiding unnecessary cost at later stages of product development. Traditionally, DFA practices are generally grouped into two categories known as qualitative and quantitative methods. Qualitative methods present the designer with rules and guidelines accompanied by illustrated examples (Andreasen et al. 1983, Laszcz 1985). Quantitative methods are associated with time periods, costs and numerical codes assigned to various part characteristics and assembly operations (Boothroyd and Dewhurst 1983, Miyakawa and Ohashi 1986, Poli and Fenoglio 1987). The qualitative approach is considered too general for practical application as it does not represent a distinct methodology, even though it incorporates product level guidelines. It is considered as an individual part level procedure for existing assemblies rather than as a product level design tool. The qualitative DFA methods include conceptual guidelines and clearly specify that the selection of adequate structuring principles for the product should precede the treatment of individual components.

On the other hand, the quantitative approach involves physical or hypothetical disassembly of the product, such as filling out a standard form in which individual components constitute separate entries. Each part is then analysed with the purpose

<table>
<thead>
<tr>
<th>No.</th>
<th>Automotive Industry (e.g. Car)</th>
<th>Machine Tool Industry (e.g. CNC Machine)</th>
<th>Electronic Industry (e.g. Mobile Phone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Many components</td>
<td>Many components</td>
<td>Small number of components</td>
</tr>
<tr>
<td>2.</td>
<td>Large number and different type of fastening and joining operations</td>
<td>Large number and different type of fastening and joining operations</td>
<td>Small number of fastening and joining operations</td>
</tr>
<tr>
<td>3.</td>
<td>Assembly tasks more complicated</td>
<td>Assembly tasks more complicated</td>
<td>Assembly tasks less complicated</td>
</tr>
<tr>
<td>4.</td>
<td>Heavy weight</td>
<td>Very heavy weight</td>
<td>Light weight</td>
</tr>
<tr>
<td>5.</td>
<td>Moving line assembly (track)</td>
<td>Central assembly</td>
<td>Work station assembly</td>
</tr>
<tr>
<td>6.</td>
<td>Many specialised tools needed for assembly</td>
<td>Many general purpose tools needed for assembly</td>
<td>Less tools and equipment are required</td>
</tr>
<tr>
<td>7.</td>
<td>Very high volume products</td>
<td>High volume products</td>
<td>High volume products</td>
</tr>
</tbody>
</table>

Table 1. Some product assembly attributes for different types of industry.
of improving its structure for easier assembly, sometimes eliminating the part from
the product. Numerous DFA case studies show that the more impressive ones are
those describing configurative-level improvement of complete products. However,
the quantitative DFA methods are inherently capable of handling individual parts
only, merely allowing for implicit product configuration improvement by elimination
or integration of parts. However the basic weakness of both qualitative and quanti-
tative approaches, when viewed as design aids, is in proposing remedies to awkward
and difficult assembly operation. Quantitative methods rarely give clues to that, and
while qualitative methods offer a variety of solutions, usually some are applicable to
the problem at hand, and some not (Kroll et al. 1989).

According to Mo et al. (1999), DFA should facilitate assembly by designing the
product throughout with procedures that simplify the composition of the product by
minimizing part numbers. In addition, they also emphasized the need to simplify
assembly operations such as handling, feeding, insertion, etc, and also to quantify
the assemblability of the product.

2.1. Development of DFA methods

In the late 1960s, a new way of thinking started to permeate through US indus-
tries (Boothroyd 1994). Many executives misunderstood customer loyalty, and were
creating new products with a 1950s’ mentality. During this period, the designers did
not take into consideration the needs of manufacturing and assembly in their design,
and finally it affected product quality (the ‘over the wall’ approach), and also caused
problems in manufacturing to specification. In addition, top management forced the
manufacturer to produce product that required additional time and equipment to
meet the specification. The manufacturers wanted the designers to hear their manu-
facturing and assembly problems that had been encountered in the earlier product
design stage. The results were frequent fire fighting in the factory and a customer still
unhappy with product quality, performance, etc.

As global competition increased in the 1970s, manufacturing sectors were pres-
sured to accept new product designs with little concern for producibility. In the 1980s
it became clear that product design drives the total business from a cost point of
view. If the assembly and manufacturing issues could be addressed in decisions taken
in the early stages of design, the potential of cost saving and design rationalization
would be higher. Eighty percent of the cost associated with a product is defined in
the design stage of product life cycle (Andreasen 1988, Leaney and Wittenberg 1992,
around 1980, and it was not until then that the significant benefits brought about
by the use of DFA were realized. As the value of DFA became recognized in the
1980s, several methods or techniques were devised with somewhat different aims in
mind. Some techniques and methods were developed for use in DFA analysis such as
the Boothroyd–Dewhurst DFA method, the Lucas DFA method, the Hitachi
Assembly Evaluation Method (AEM), the Integrated Design For Assembly
Evaluation and Reasoning System (IDAERS), etc. Leaney and Wittenberg (1992)
conducted a comparative study of the Boothroyd, Lucas and Hitachi methods. In
addition, a case study was presented using each of them. The conclusion of the work
was that the design efficiency of the Lucas method is based on the scope for reducing
the number of parts, while the Boothroyd method is concerned with reducing the
number of parts and improving handling and insertion processes. In the Hitachi
method, efficiency is based on the insertion processes. Table 2 shows some of the established DFA methodologies and systems in manufacturing industries.

3. Assembly planning

Assembly planning is concerned with creating assembly sequence steps based on connectivity relationships between the component parts from which a product is assembled (Wang and Li 1991). It deals with the application of algorithms and heuristic rules to produce alternative feasible assembly plans. Yuan and Li (2000)

<table>
<thead>
<tr>
<th>No.</th>
<th>Tools</th>
<th>Year</th>
<th>Researchers</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Lucas DFA</td>
<td>1980</td>
<td>Redford, A. H. and Swift, K. G.</td>
<td>This is based on Assembly Sequence Flowchart (ASF) to evaluate assembly design. It involves assigning and summing penalty factors associated with design problems.</td>
</tr>
<tr>
<td>2.</td>
<td>Hitachi Assemblability Evaluation Method (AEM)</td>
<td>1986</td>
<td>Miyagawa, S. and Ohashi, T.</td>
<td>This method makes use of assemblability and assembly cost ratio indices to identify the weak points of a design. There is no distinction between manual and automated assembling and centres on insertion operations for components</td>
</tr>
<tr>
<td>3.</td>
<td>Product Assemblability Merit Analysis Tools (PDM)</td>
<td>1986</td>
<td>Zorowski, C. F.</td>
<td>This tool is used for rating product and part designs on assembly difficulty and redundancy criteria</td>
</tr>
<tr>
<td>4.</td>
<td>Boothroyd and Dewhurst</td>
<td>1988</td>
<td>Boothroyd, G. and Dewhurst, P.</td>
<td>This method is based on empirical study of the cost associated with assembly process, manual, robotic or automatic, and addresses three criteria for reduction of part numbers.</td>
</tr>
<tr>
<td>5.</td>
<td>Integrated Design for Assembly Evaluation and Reasoning System (IDAERS)</td>
<td>1991</td>
<td>Sturges Jr, R. H. and Kilani, M. I.</td>
<td>This is built on an existing solid modelling package to evaluate the assemblability of the design and to recommend design modification to decrease the assembly time and the level of difficulty</td>
</tr>
<tr>
<td>7.</td>
<td>DFA REV-ENGE</td>
<td>1994</td>
<td>Kim, G. J. and Bekey, G. A.</td>
<td>Design For Assembly by Reverse Engineering</td>
</tr>
<tr>
<td>8.</td>
<td>Constraints Network System</td>
<td>1995</td>
<td>Oh, J. S., Grady, P. O. and Young, R.DF</td>
<td>A knowledge expressed as interrelated constraints</td>
</tr>
</tbody>
</table>

Table 2. DFA methodologies and systems.
said that the main purpose of assembly planning is to arrange and organize a proper sequence with which the components can be grouped and fixed together to form a final product. In other words, assembly planning is the procedure of generating an optimal sequence to assemble a product. The relationship between the components of an assembly can be represented using a hierarchical structure. Yuan and Li (2000) summarized assembly planning in three stages: assembly modelling and representation, assembly sequencing and assembly analysis and evaluation. Tonshoff et al. (1992) listed some rules and priorities, such as task-related rules, object-related and organizational rules as a strategy for determining the optimum assembly sequence.

There is extensive literature and research work reported in the area of assembly sequence generation to help product assemblability. Sanderson and Homem de Mello (1990) proposed a decomposition approach using AND/OR graphs. They also developed an algorithm (Sanderson and Homem de Mello 1991) that takes a description of the assembly and returns the AND/OR graph representation of the assembly sequence. On the other hand, Wolter (1991), used a constraint graph to represent the precedence relationship in an assembly sequence. Huang and Lee (1989), used the feature mating operation graph. Santochi and Dini (1992), applied the contact graph and the incidence matrix. Lin and Chang (1993) published a complete review in which an integrated approach to assembly planning using graph representation forms was developed. They used a three-layer strategy and a special tree structure to represent assembly and generate one feasible sequence. Most researchers use traditional graph search approaches to find an assembly sequence, but due to increases in the number of product parts and complexity, the search increases explosively, resulting in severe combinatorial complexity (Fujimoto and Sebaaly 2000).

To overcome the above complexity, a number of researchers used a knowledge-based heuristic or Hopfield Neural Networks (NN) approach to develop a feasible assembly sequence. Delchambre and Wafflard (1990) generated precedence orders found from a backward planning approach. Swaminathan and Barber (1996) used a case-based reasoning approach and proposed a plan reuse philosophy to generate assembly plans. The main disadvantage of the NN approach is that one or more valid sequences must be provided to train the network before the search can be performed (Fujimoto and Sebaaly 2000). Milner et al. (1994) used Simulated Annealing (SA) to overcome the above disadvantage. However, this was unable to give optimum results in performing a complete set of feasible assembly evaluations. De Fazio et al. (1997) and Sebaaly and Fujimoto (1996) used genetic algorithms to generate the best assembly sequence plan. In addition, Ben Arieh and Kramer (1994) proposed a methodology and algorithms to generate all feasible assembly sequences by the various combinations of subassembly operations. A LISP program was used for implementing the algorithms. Ben Arieh (1994) used a fuzzy set based method to evaluate the degree of difficulty of each assembly operation and then select the best sequence of assembly operations. However, in the view of Choi et al. (1998), these methods and algorithms are less interactive and need much more space to store the representations of assembly sequences, and also need much more computing time to process the assembly operations for complex assemblies. It also seems difficult to generate detailed assembly plans automatically and to deal with the coordination and feasibility of various subassemblies efficiently. Therefore, they proposed a new approach and system for the automatic generation of assembly sequences. It is based
on assembly knowledge or information and the method of determination and
decomposition of feasible subassembly subsets. An automatic knowledge reasoning
system based on artificial intelligence was developed to generate the assembly
sequences.

Research activity has also been conducted in the area of concurrent assembly
design rather than independent sequence generation and component design. Li and
Hwang (1992) recognized this gap and proposed a system that linked an assembly
sequence generation module, a DFA analysis tool and a redesign suggestion applica-
tion. Hsu et al. (1993) examined how data generated at the assembly planning stage
could produce redesign suggestions. Kim et al. (1995) proposed ISPIRE-2, which
integrates assembly planning, DFA and a redesign module. Barnes et al. (1997)
proposed a user interface for interactive generation of assembly sequences more
proactive to DFA in a solid modelling environment, invoking function and accessing
information from a product model, and which is used concurrently within the design
process.

Delchambre (1990) listed five types of information required for generating an
assembly plan: component geometry, component attributes, final assembly informa-
tion (assembly directions), topology and technological aspects (additional con-
straints). Thus, the description of an assembly to the computer in terms of
geometric relationships and physical constraints is a critical problem and is crucial
for automatic assembly planning. The geometric input to the system can be provided
by features that can identify connections between parts making up the assembly. Ye
and Urzi (1996) said that most existing assembly planning systems consider only
hard constraints based on geometry and topology and overlook soft constraints such
as weight, part size, etc. They highlighted that human intelligence and artificial
intelligence need to collaborate, which leads to the development of assembly decision
support systems rather than completely automated assembly planning systems.

Kunica and Vranjes (1999) supported the view that human interaction should
always be present and seen as an important aspect in the decision process because
it is difficult or non-rational to reduce to an algorithm.

Many knowledge-based systems have been developed for assembly planning, as
they are suited to handling a large amount of data and the existence of insufficient or
ambiguous information. Lim et al. (1995) reviewed research work in computer-based
environments for supporting the concurrent design of products and assemblies. The
review also discussed the roles of feature and mechanical assembly modelling in
providing an effective environment for the design of components and assemblies.

4. Assembly modelling

4.1. Assembly representation

Henson (1999) reviewed work on assembly representation and classified it under
the following six headings.

(a) Hierarchical model and assembly sequences—representing the earliest form
of computer assembly models.
(b) Relational models and assembly languages—used by commercial solid
modelling systems to describe the mating conditions and using a largely
bottom-up approach.
(c) Feature-based assembly modelling—the problems of using features to
integrate data about function, behaviour and physical structure.
(d) Modelling function—functional languages demonstrating the support of design intent.

(e) Representation behaviour—quality reasoning providing a distinction between function and behaviour. The bond graph modelling notation unifies the modelling of dynamics systems and can be used for analysis and qualitative reasoning.

(f) Computer Aided Engineering (CAE) systems to support product development—computer systems made from a number of applications intended to support product development.

Detailed explanation and literature support of each assembly representation mentioned above can be found in Henson (1999). Zha et al. (1998a) held the view that assembly representation can be categorized into three approaches, namely language-based representation, graph-based representation and advanced data representation. However, the graph-based representation is more general and usually extracts data from more information sources, such as a CAD database or from information supplied by the user. It is represented in numerous forms, for example directed graphs, AND/OR graphs, connectivity graphs, hierarchical partial order graphs, liaison diagrams, precedence diagrams, assembly constraints graphs and interference graphs. The above forms of representation have been discussed earlier.

4.2. Assembly modelling

Fujimoto and Sebaaly (2000) stated that assembly modelling starts with a CAD design model of a product and generates a set of connections between products, parts, and a set of functional precedence constraints between these connections. Zhao and Masood (1999) defined assembly modelling as ‘a procedure for describing the assembled state of a given product assembly in terms of its basic assembly connections’. Case and Wan Harun (1997) inferred that assembly modelling deals with the interrelations among assembled parts rather than the detailed shape of each part. Gui and Mantyla (1994) reported that functional understanding of assembly modelling is a key step towards a real CAD environment that can support the early stages of design. Usher (1993) supported the view that the capability to represent products composed of assemblies is needed to support further integration of manufacturing systems in order to provide data for assembly sequencing and analysis.

Mantyla (1990) developed a top-down modelling system to aid design engineers in the preliminary design process. Based on this top-down approach, modelling techniques that support design of assemblies have been developed. The top-down assembly modelling approach is based on generating a functional or symbolic description of a prospective design (conceptual synthesis of a new system). The functional model should be validated before moving into individual part design. The bottom up approach is used when the detailed designs of parts of the assembly are available. This starts with component design followed by continuous use of abstraction and refinement, mixed with both top-down and bottom-up approaches to assembly design. According to Jianzhong et al. (1999), a DFA oriented assembly model should include three elements to be considered as part of assembly modelling. The three elements are

- Functional model: to describe the functions of products and components, the function–function relation and function-part deployment relation.
• **Geometry model**: to describe the contacting and positioning relationship among parts.
• **Connecting model**: to describe the connecting methods.

One more element is a product model, which describes a product composition, representation and relation based on feature modelling technology. Table 3 shows reported research on assembly representation.

### 4.3. Assembly in MOSES project

MOSES (Model-Oriented Simultaneous Engineering Systems) was a collaborative project between the Departments of Mechanical Engineering, University of Leeds and Manufacturing Engineering, Loughborough University. An important contribution of the MOSES project is the Product Model, which supports several applications. It is modular to facilitate change and control of change. Three types of

<table>
<thead>
<tr>
<th>No.</th>
<th>Researchers</th>
<th>Area</th>
<th>System/methodology used or developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Lieberman and Wesley (1977)</td>
<td>Assembly representation</td>
<td>AUTOPASS</td>
</tr>
<tr>
<td>2.</td>
<td>Popplestone et al. (1978)</td>
<td>Assembly representation language</td>
<td>PART</td>
</tr>
<tr>
<td>3.</td>
<td>Wesley et al. (1980)</td>
<td>Assembly modelling of assembly</td>
<td>GDP</td>
</tr>
<tr>
<td>4.</td>
<td>Eastman (1981)</td>
<td>Assembly representation</td>
<td>Location graph</td>
</tr>
<tr>
<td>5.</td>
<td>Lee and Gossard (1985)</td>
<td>Assembly representation</td>
<td>Virtual links</td>
</tr>
<tr>
<td>7.</td>
<td>Woo (1987)</td>
<td>Assembly sequence generation</td>
<td>Disassembly</td>
</tr>
<tr>
<td>12.</td>
<td>Huang and Lee (1989)</td>
<td>Assembly sequence generation</td>
<td>Feature mating operation graph</td>
</tr>
<tr>
<td>13.</td>
<td>Lin and Chang (1990)</td>
<td>Assembly representation, assembly process planning</td>
<td>Solid model, frame based</td>
</tr>
<tr>
<td>14.</td>
<td>Homem de Mello and Sanderson (1990)</td>
<td>Assembly representation, sequence generation</td>
<td>AND/OR graph</td>
</tr>
<tr>
<td>15.</td>
<td>Mantyala</td>
<td>Assembly modelling of assembly</td>
<td>Top down</td>
</tr>
<tr>
<td>17.</td>
<td>Santochi and Dini (1992)</td>
<td>Assembly sequence generation</td>
<td>Contact graph and incidence matrix</td>
</tr>
<tr>
<td>18.</td>
<td>Ben Arieh</td>
<td>Assembly sequence generation</td>
<td>Fuzzy set based method</td>
</tr>
<tr>
<td>19.</td>
<td>De Fazio et al. (1997)</td>
<td>Assembly sequence generation</td>
<td>Genetic algorithms</td>
</tr>
</tbody>
</table>

*Table 3. DFA work on assembly modelling of products (adapted from Jhong et al. 1995).*
module are required for an integrated data model: the overall framework, application data and shared models (McKay and Bloor 1991, McKay 1993).

The objective of the assembly data work package of the MOSES project was to develop a data model that could represent mechanical assemblies in a distributed working environment where data are shared between applications. In the MOSES project, Henson (1995) referred to assembly models as a 'constituent of information systems that will provide the product and manufacturing data necessary to integrate product design and process design'.

As a result of the previous project, Leeds University produced a product data framework called the Structure Editor (Henson et al. 1993a) that considered assemblies as lists of parts without reference to physical or functional connectivity. This framework was suitable for Bill Of Material (BOM) applications, but with the limitation of being less useful where geometry applications were required. Therefore, one of the goals of the MOSES project was to create new structures to support information about assemblies required by applications throughout the life cycle of the product.

In addition, the MOSES Project followed up the work of Mantyla (1990) on the need for providing information to support the assembly information at different levels of abstraction. The MOSES project developed an assembly data model able to support enquiries about component degrees of freedom, their material specification and their assemblability. The research in the assembly modelling work package followed steps to define language-neutral assembly mating conditions and development of a data model to describe behaviour (Henson 1995). These resulted in the development of a data model that supports the description of the mating conditions relying on degrees of freedom. Bond graph notation was chosen to describe behaviour, and a database and applications were developed to demonstrate that descriptions of structure and behaviour were, to a certain extent, integrated.

Whitney (1996), inferred that an assembly model must be capable of capturing the information needed to describe the entities and activities associated with assemblies and assembling. This information must be useful for designers of products, assembly systems and logistic systems as well as for suppliers, field support, disassembly and recycling.

5. Artificial intelligence and knowledge-based approaches in assembly

Recently, more researchers have been active in the area of applied knowledge base and artificial intelligence (AI) techniques to assist in solving design for assembly problems. Several knowledge-based expert methodologies and systems have been developed, e.g. DFAES (Design For Assembly Expert System) by Zha et al. (1999), which uses a knowledge-based approach and implements an expert system for integrated product design for assembly, IDAERS (Integrated Design for Assembly Evaluation and Reasoning System) by Sturges and Kilani (1992) and CAAPP (Computer Aided Assembly Process Planning) by Molloy et al. (1991). Zhao and Masood (1999) presented an intelligent computer aided process planning system (ICAAPP) for generating and optimizing assembly sequences for mechanical parts. The system employs a graph set technique for creating an assembly model.

Other rule-based and knowledge-based DFA systems have also been developed, such as ADAM (Assisted Design For Assembly and Manufacture) by Sackett and Holbrook (1988), and PACIES (Part Code Identification Expert System) by Chen and Young (1988). Ishi et al. (1988) presented DCA (Design Compatibility
Analysis). LUCAS Engineering (Expert System Opportunities 1990) developed the famous knowledge-based design for assembly system that generates guidelines on minimizing the number of parts and simplifying insertion. This system is considered the most advanced in DFA, although it is not necessarily the most effective for reducing assembly cost. The work by Swift (1987) was oriented towards advising the designer of difficulties in estimating the cost of handling of components, suggesting solutions and estimating the cost of the required handling equipment. Jakiela (1989) and Jakiela and Papalambros (1989) developed an intelligent CAD-DFA system. They suggested integrating a knowledge-based DFA consultant system in a conventional computer aided design (CAD) environment. The system was encoded from the Boothroyd DFA knowledge base with feature-based representation, and it responds to users with suggested design improvements. Kroll et al. (1989) took a different approach to assist design for assembly by proposing a knowledge-based consultant system that incorporates models of the product and of the assembly process and operates according to a model of the human design processes. It is capable of offering relevant and intelligent advice to the designer.

6. Decision Support System (DSS) in assembly

Research work on decision support systems (DSS) was started in the 1960s (Klein and Methlie 1990). DSS contributions become very valuable for the manufacturing industries in making decisions to ease their problems. Radermacher (1994) mentioned that DSS has stimulated great interest in research and its application area. He emphasized the point that decision making is one of the essential tasks that mankind must deal with continually on every level.

Wang (1997) described DSS as a computerized information system that contains domain specific knowledge and analytical decision models that assist the decision maker by presenting information and the interpretation of various alternatives. Santana (1995) added that a DSS is intended to enhance individual decision-making by providing easier access to problem recognition, problem structure, information management, statistical tools and application of knowledge. Sprague and Carlson (1982) defined DSS as computer-based systems that helps decision makers confront ill-structured problems through direct interaction with data and analysis models. Another classic definition of DSS, provided by Keen and Scott Morton (1978), mentioned that a DSS couples the intellectual resources of individuals with the capabilities of the computer to improve the quality of decisions. It is a computer-based support system for management decision makers who deal with semi-structured problems.

Bonczek et al. (1980) referred to DSS as a computer-based system consisting of three interacting components: a language system (a mechanism to provide communication between the user and other components of the DSS), a knowledge system (the repository of problem domain knowledge embodied in DSS, either as data or procedures), and a problem-processing system (the link between the other two components, containing one or more of the general problem manipulation capabilities required for decision making). Yam et al. (2001) reported that a DSS is designed to enable easier and faster generation of alternatives, and to increase the awareness of deficiencies in the decision making process. Moreover, the DSS can assist the decision maker to make more effective and efficient decisions in complex and critical situations.
A number of computational tools have been developed for DSS such as knowledge bases, analytic hierarchy processes, Petri nets, neural networks, fuzzy logic and fuzzy networks and Bayesian theory.

Figure 1 describes how the current assembly model has been supported by computer software and knowledge-based approaches. It starts with assembly methodology as a core part of the overall assembly procedures, which consist of assembly system/process selection, DFA and assembly planning. The left and right sides of the core assembly methodology show how the methodologies have been supported by software and knowledge-based or AI tools respectively. This is illustrated by the large arrows shown in outline, which indicate the existence of support links at each core level of the assembly methodology. For example, the Toolkit software developed by Boothroyd and Dewhurst (1992) mentioned in the earlier part of this paper is used to assist in assembly process selection.

DFA is the primary activity in product design, and is employed to simplify a product structure so as to reduce assembly and total part costs. Therefore, computer support software, such as B&D DFA Method, TeamSet (Lucas), Hitachi (AEM), PDM, etc has been established to enhance DFA activity. Some intelligent and knowledge-based support such as DFAES and IDAERS has been developed to expedite the DFA process.

Assembly planning is another important area in assembly methodology that has a strong, influence on assembly system and product design, and the cost of assembly either directly or indirectly. The selection of an efficient set of assembly representations, sequences or models is important in assembly planning. Therefore, much

![Figure 1. Current support for assembly methodologies, and potential contributions from extended knowledge-based support.](image)
research work has focused on the various aspects of assembly planning. Various approaches and tools such as AND/OR Graph, Bond Graph, Contact Graph, Top Down, Liaison Graph, Feature Mating Graph, Simulated Annealing etc have been developed to implement it. Substantial research work has also been involved in the use of knowledge-based or AI approaches in assembly planning. Some of the approaches are CAAPP, ICAAPP, ADAM, DCA, PACIES and Intelligent CAD-DFA.

However, there seems to exist a gap in knowledge-based or AI support for assembly process or system selection. This is highlighted in figure 1, where the opportunity for intelligent software support in assembly process selection to bridge the gap is shown as an empty box.

The gap is further emphasized by figure 2, which illustrates the relative frequency of published research, distinguishing between those developing either conventional, knowledge-based or AI (KB/AI) support tools in the fields of research shown in figure 1; namely, Assembly System/Process Selection (AS/PS), Design for Assembly (DFA) and Assembly Planning (AP). Totals are also shown. Papers have been included in a category if they present some development in the field. Where papers propose and develop integration of ideas in two or more fields, these have been counted in both (all) fields. References to fields without new development, appearing in a paper for comparison or review purposes, are not counted in the figure. Thus, figure 2 displays contributions to the fields. It is clear from the figure that DFA is the most researched topic, whilst AS/PS has been least studied with no KB/AI methods proposed to date.

Although much literature and research have been published emphasizing DFA and assembly planning as a part of the assembly methodology process, there is no corresponding research on AI or knowledge-based support. Assembly process selection may have the greatest impact on cost of production, but the literature shows that very few issues are addressed in this area. Zha et al. (1998b) agreed in their literature review that there is a lack of methods and AI or knowledge-based support to address this issue. However, there are growing applications of artificial intelligence, such as expert systems, fuzzy logic, neural networks, and genetic algorithms, to assembly line balancing and equipment selection. The research work done by
Boubekri and Nagaraj (1993) proposed an integrated approach for selecting a feasible method of assembly and the selection of assembly technologies for a given product. However, the research addressed only how to choose manual or flexible assembly for a given product by considering factors such as annual volume of product, number of variants, product life and number of component parts. No AI or knowledge-based elements were incorporated to assist the assembly technology and system selection. Abdel-Malek and Resare (2000) presented research on DSS and AI tools, but covered only a limited area of assembly process activities. They developed an analytical model with algorithms and DSS to aid the decision-maker in the selection of machines and robots related to assembly cell components.

Since little work has focused on knowledge-based or AI support for the assembly system or process selection area, figure 1 offers a new opportunity for AI or knowledge-based support for this process. The relationship between the empty box and assembly methodology processes, software and knowledge-based or AI support is indicated by black arrows. Following the arrows, the empty box provides intelligent support in selecting tools for use in other stages of the assembly activities. The use of knowledge-based or AI support enhances information support during the assembly process or system selection stage specifically and the entire process in general. Intelligent support here should be able to provide users with intelligent advice or suggestions in order to obtain improved, highly efficient assembly methodology selection. The same mechanism can be applied to other parts of assembly methodology selection, such as the product design (DFA) and assembly planning stages. There is a need to identify, by a decision support system, the best software support and knowledge-based tools to fit each level of the assembly methodology. The arrows in figure 1 show the correlation at each level of assembly. It is proposed that a suitable intelligent knowledge-based support tool can be designed to fill the gap that exists in selecting an assembly paradigm, and which could be extended to assist in selection of appropriate tools from the available range to support the subsequent steps in assembly methodology.

7. Conclusions

An intelligent decision support system could impact on many areas of the assembly methodology. It is envisioned that, at its highest level, such a tool can interpret manufacturing strategy expressed in terms of product characteristics, market, and projected production volumes, and provide guidance to appropriate assembly systems. As a project develops, lower-level extensions of the same tool might have the capacity to propose relevant techniques and tools for use in DFA and assembly planning. This will take into account process selection decisions already committed.

The authors would not anticipate such a decision support system being implemented as a fixed, hard-coded, software tool. Rather, it would take the form of a knowledge-based system in which the current assembly methodology expertise is held in a knowledge base that can be extended or amended as ideas develop, either in the particular company, or as a response to changes in current technology or perceived best practice. This structure would also permit the creation of specialized versions of the decision support system to be applied in different industrial environments: for example the knowledge needed to reason about the assembly of heavy, unmanageable products such as machine tools would be redundant in a company manufacturing portable power tools. In this latter environment, such
knowledge could be omitted, and substituted by more detailed knowledge about, say, bench assembly, not needed for machine tools.

As product introductions become more frequent in response to increasingly volatile and competitive markets, decisions on assembly methodology become both more frequent and more critical to future profitability. The decision support system as proposed here could offer the ability to recognize and retain relevant knowledge, which at present may reside in the experience of just a few experts. Thus, knowledge is protected and potentially made available to a wider range of less experienced engineers, providing an increased capacity to support new product introduction.

References


Boothroyd, G. and Dewhurst, P., 1983, Design for Assembly—A Designer’s Handbook, Department of Mechanical Engineering, University of Massachusetts, Amherst.


Henson, B., 1995, Assembly Modelling Workpackage Final Report, MOSES Project (University of Leeds, and Loughborough University, UK).


